The geological history of the North Atlantic Ocean

GODFREY FITTON
DEPARTMENT OF GEOLOGY AND GEOPHYSICS,
UNIVERSITY OF EDINBURGH

AND

LOTTE MELCHIOR LARSEN
GEOLOGICAL SURVEY OF DENMARK AND GREENLAND, COPENHAGEN
AND DANISH LITHOSPHERE CENTRE, COPENHAGEN

The North Atlantic Ocean began to form about 130 million years (Ma) ago when sea-floor spreading, propagating from the south, caused Iberia and Newfoundland to separate. At that time, the crust beneath the region was stretching and subsiding to form sedimentary basins (including the North Sea). By ~105 Ma, sea-floor spreading had extended into one of these basins, the Rockall Trough, and this continued until ~84 Ma. Spreading started again further west to form the Labrador Sea at ~61 Ma, and then between Greenland and Scotland at ~56 Ma. Unlike the earlier rifting episodes, the final stage in the break-up of the North Atlantic region was accompanied by the widespread eruption of basaltic magma. Two phases of magmatism are recognised: the first (62-58 Ma) predating the separation of Greenland from NW Europe, and the second (56-52 Ma) accompanying it. The sudden onset of volcanism at 62 Ma was due to the initiation of a convective plume of hot mantle, now located beneath Iceland. The products of the two volcanic phases are preserved as thick sequences of basaltic lava flows outcropping over an area extending from Baffin Island in the west, through West and East Greenland and the Faeroes, to Scotland in the east. The second phase blanketed large parts of western Europe with volcanic ash layers that now form important stratigraphic marker horizons in the North Sea and surrounding areas, including Denmark and Great Britain.

Initiation of the Iceland mantle plume caused regional uplift and may have influenced the final stages of continental break-up. Uplift led to erosion of the continental margins and the deposition of hydrocarbon-hosting sand bodies in the North Sea, and is also responsible for shaping the landscape of the Atlantic margins.

Introduction

The idea that continents can move around the surface of the Earth was first proposed as a serious scientific theory by Wegener (1915). He used the striking similarity in the shape of coastlines on opposite sides of the Atlantic Ocean, coupled with an impressive body of geological and climatological evidence, to argue that the continents had been united, 200 million years (Ma) ago, into one supercontinent that he called *Pangaea*. Since this time, he argued, *Pangaea* has broken up and the continents have slowly drifted into their present configuration. Wegener's (1915) continental drift theory divided the geological world into followers and opponents who debated the issue until the 1970s. Opposition to the theory was based mostly on the lack of a viable mechanism for the movement of continents and on the belief that the Earth behaved as a rigid solid. A mechanism was offered by Holmes (1931) who proposed that continental drift is driven by convection currents in the mantle (that part of the Earth beneath the crust). He argued that heat from the decay of radioactive elements provided much of the energy to sustain mantle convection. Although the mantle is solid, it behaves as a viscous fluid and is capable of convection through the process of solid-state creep – the process that allows solid ice to flow in glaciers. Holmes (1931) was the first to suggest that continents ride passively on the mantle; earlier workers had assumed that the continents somehow ploughed their way across the ocean floors.

By the late 1950s the ocean basins had been mapped in enough detail to reveal the continuity and length of the mid-ocean ridges (e.g. Menard, 1958; Heezen *et al.*, 1959). Significantly, the Mid-Atlantic Ridge was shown to run down the centre of the Atlantic Ocean and parallel to the coastlines on either side (Heezen *et al.*, 1959). This led Hess (1962) to suggest that mid-ocean ridges represent the sites of convective upwelling of the Earth's mantle and that the ocean crust is spreading symmetrically away from the ridges, rather like pairs of conveyor belts. Proof of Hess's (1962) sea-floor spreading hypothesis was provided by Vine & Matthews (1963) through their interpretation of magnetic anomalies in the oceans, and this led to the establishment of plate tectonics as a unifying theory in the Earth Sciences.

The Earth's surface is made up of rigid plates, about 100 km thick, called the lithosphere. These plates are composed of crust and upper mantle and are underlain by a layer of ductile but solid mantle known as the asthenosphere. The plates move with respect to each other and are driven partly by convective motion of the asthenosphere. Estimates of the rate and direction of plate motion have allowed accurate reconstruction of the ocean basins and continents since the break-up of *Pangaea*. In this paper we shall give a brief geological history of the North Atlantic Ocean and show how its surrounding land masses acquired their present configuration and topography.

The formation of ocean basins

As lithospheric plates are pulled apart, the asthenosphere wells up to fill the space created and partially melts to produce basaltic magma. Some of this is erupted onto the sea floor, but most is injected as dykes (narrow, vertical, sheet-like intrusions) or remains at the base of the new crust to crystallise as gabbro (coarse-grained equivalent of basalt). Thus the ocean crust grows from the axis of the mid-ocean ridges as the plates move apart, and the unmelted residue of the upwelled asthenosphere cools, becomes rigid, and forms part of the new lithospheric plate as it spreads away from the ridge. Since the Earth's surface area is constant, oceanic lithosphere must be destroyed at the same rate as it is created, and this occurs when it is eventually returned to the deeper mantle at ocean trenches through a process known as subduction. Because the lithosphere is colder and more dense than the asthenosphere, the subduction process contributes to the forces that cause plate motion. Subduction ensures that the ocean crust is recycled back into the mantle on a time scale that is short in comparison with the age of the Earth, and the ocean crust is therefore very much younger than most of the continental crust. The oldest ocean crust on Earth (in the western Pacific Ocean) has been dated at about 180 Ma, whereas the oldest recorded continental rocks (in Arctic Canada) have ages of around 4000 Ma.

Although most aspects of Hess's (1962) sea-floor spreading hypothesis have become accepted, we now know that the mid-ocean ridges do not represent the rising limbs of deep-mantle convection cells, but form as a passive response to the pulling apart of plates. The convective upwelling that helps to drive plate motion is largely independent of the global system of mid-ocean ridges and subduction zones and takes the form of plumes of hot mantle rising from deep within the Earth. One such plume is responsible for the Hawaiian island chain in the middle of the Pacific plate, and another coincides with the Mid-Atlantic Ridge to form Iceland.

Why continents break up to form new ocean basins is still the subject of debate, but it is widely believed that stresses imposed on the base of the continental lithosphere by the motion of the asthenosphere, combined with the pulling effect of subduction, can cause the lithosphere to stretch and ultimately break. In some cases, though, it is clear that mantle plumes can either trigger break-up or influence its progress. As we shall show later, the Iceland plume has had an important influence on the shaping of the North Atlantic Ocean.

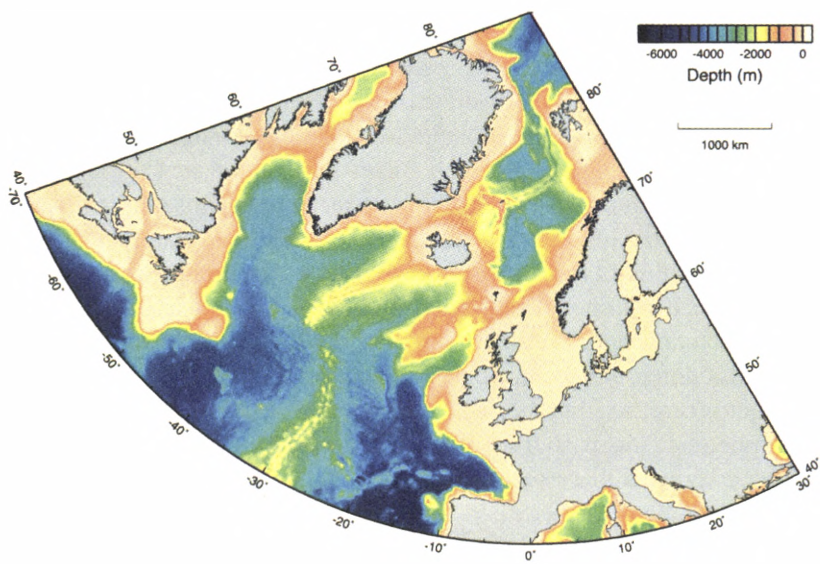

Figure 1. Bathymetry of the North Atlantic Ocean, based on the ETOPO5 (Earth Topography – 5 Minute) digital data base compiled by the U.S. Naval Oceanographic Office.

Bathymetry of the North Atlantic Ocean

Wegener (1915) was impressed by the way the coastlines around the Atlantic Ocean fit together, but coastlines are only transient features, the location of which depends on relative sea level. The outer edges of the continental shelves are the true margins of the continents. Figure 1 shows the bathymetry of the North Atlantic Ocean and it can be seen from this map that the continental shelves end on steep slopes where the ocean depth increases abruptly from <2000 m to >4000 m. Several other features seen on this map are important to an understanding of the geological development of the North Atlantic.

1. The continental shelf of north-west Europe does not always run parallel to the coastline, but contains several deep embayments. The most prominent of these is the Rockall Trough to the west of Scotland. Here, a continental fragment, Rockall Bank, appears to have broken away from the continental shelf. Jan Mayen (NW of Iceland) and the Faeroes lie on smaller continental fragments. Note also that the continental shelf around the Iberian Peninsula and south-west France is very narrow and that the Bay of Biscay is truly oceanic in its water depth.
2. The continental shelf of West Greenland is separated from that of Labrador and Baffin Island by a narrow strip of deep water (the Labrador Sea and Baffin Bay), showing that continental separation has occurred between Greenland and North America.
3. The Mid-Atlantic Ridge is seen as a prominent linear feature running the length of the ocean. The ridge is offset in several places by transform faults, the most prominent of which can be seen to the south of Spitsbergen and at about 52°N. It is the existence of these faults that provides evidence that the ridges are passive features and not the result of the rising limbs of convection cells from the deep mantle.
4. Iceland sits astride the Mid-Atlantic Ridge and is surrounded by a broad region of shallow ocean. This shallow zone forms a broad ridge extending across the ocean from Greenland to the Faeroes and is due to two effects of the Iceland plume. Firstly, upwelling of anomalously hot mantle plume material has the effect of uplifting the ocean floor. Secondly, the plume's proximity to the Mid-Atlantic Ridge, both now and over a large part of the history of the North Atlantic, has resulted in thicker-than-normal ocean crust. Normal

ocean crust has a very uniform thickness of ~7 km, whereas that on the Greenland-Iceland-Faeroes ridge is 20 to 35 km thick, comparable in thickness to continental crust (White, 1997; Darbyshire *et al.*, 1998).

Age of the North Atlantic Ocean

Vine & Matthews's (1962) explanation for oceanic magnetic anomalies led directly to a method for estimating the age of the ocean basins and for reconstructing past plate motions. The anomalies run parallel to, and are symmetrical about, the mid-ocean ridges and are caused by strips of ocean crust magnetised, alternately, in the same (normal) and opposite (reversed) direction to the Earth's present magnetic field. The magnetic field measured over the oceans is enhanced in places where the rocks on the ocean floor are normally magnetised and reduced where they are magnetised in a reversed direction. Magnetisation of the ocean crust is inherited from the Earth's contemporary magnetic field as the magma that forms new crust at mid-ocean ridges cools and crystallises. The direction of the Earth's field reverses on average every 500,000 years, although reversal intervals vary widely from tens of thousands to tens of millions of years. Continuous growth of the ocean floor, coupled with periodic reversals in the magnetic field, produces magnetic stripes that give an accurate record of the past position of the mid-ocean ridge. The magnetic anomalies thus record reversals in the magnetic field in much the same ways as tree rings record fluctuations in climate. Once the magnetic anomalies have been mapped, it is possible to reconstruct the history of an ocean basin by matching up magnetic stripes on either side of the mid-ocean ridge.

In order to assign absolute ages to the history of ocean basins deduced from magnetic anomalies, it is necessary to calibrate the reversal history of the Earth's magnetic field. This has been achieved by measuring the magnetic polarity and radiometric age of continuous volcanic successions on land (in Iceland, for example) and comparing this with the magnetic and fossil records preserved in deep ocean sediments. As a result of several decades of work, we now have a magnetic time scale extending back to about 165 Ma (e.g. Berggren *et al.*, 1995). The magnetic time scale can then be used to convert the magnetic anomaly map of the ocean basins into maps contoured by age. Figure 2 is such a map for the North Atlantic Ocean, and this map can be used to reconstruct

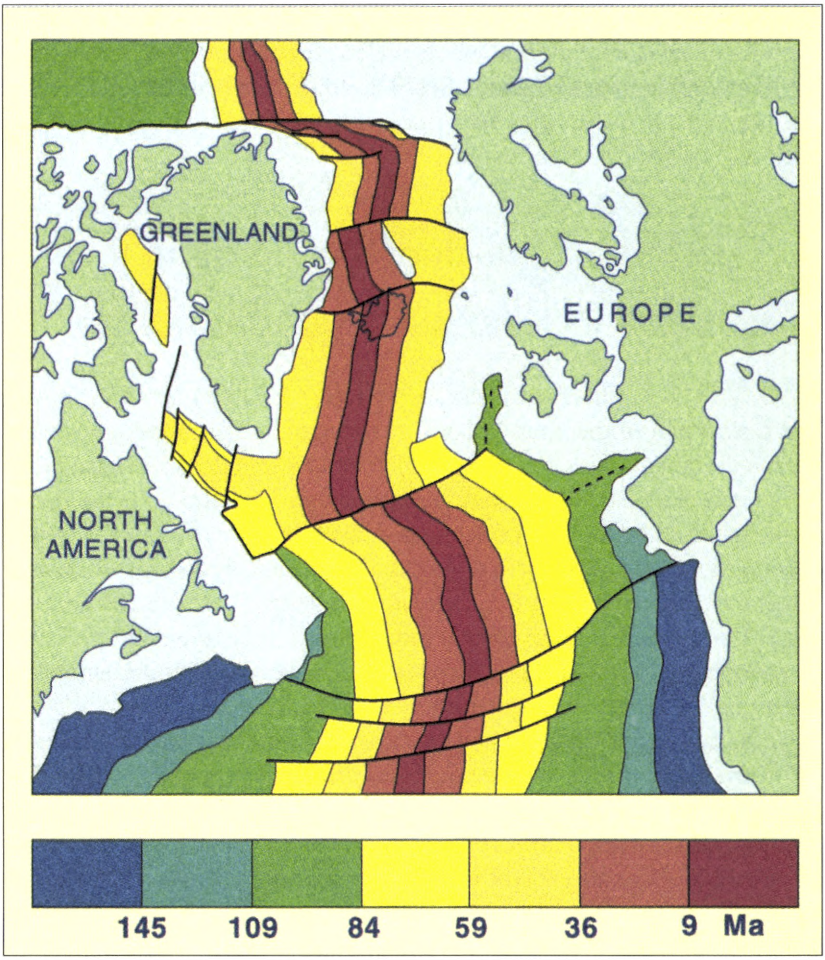

Figure 2. The age of the North Atlantic Ocean floor, based on magnetic anomalies. Broken lines in the Bay of Biscay and Rockall Trough represent short-lived spreading centres in these areas. After Ziegler (1989), with the area between Canada and Greenland modified after Whittaker *et al.* (1997) and T.C.R. Pulvertaft (personal communication, 1999).

the history of the ocean by sequentially removing age bands from the youngest to the oldest. At each stage, magnetic anomalies of the same age but on opposite sides of the Mid-Atlantic Ridge are juxtaposed to give the position of the ridge at the time the anomaly formed. Reconstructions of the North Atlantic Ocean, at six stages in its development, are shown in Figure 3. In these maps the Mid-Atlantic Ridge (shown as a double line) is only plotted where its location can be clearly identified from matching magnetic anomalies. The edge of the continental shelf is represented by thick lines that mark the position of the present-day 2000 m contour for water depth.

History of sea-floor spreading in the North Atlantic region

The early phase (130 to 62 Ma)

The oldest part of the North Atlantic formed at about 130 Ma, when the Iberian Peninsula began to rotate anticlockwise and separate from Newfoundland (Fig. 3). At this time Europe, Greenland and North America were united as a single continent, although a narrow ocean to the south separated Africa from North America. The oldest ocean crust in the Atlantic Ocean is found off the eastern coast of the United States and the west coast of Africa (Fig. 2), and the ocean floor becomes progressively younger northwards. The crust beneath the North Atlantic region had been under tension for some time before break-up, and stretching and thinning of the crust had caused the subsidence that led to the formation of sedimentary basins such as the North Sea and Rockall Trough. The rotation of Iberia led to the opening of the Bay of Biscay and, at about 105 Ma, sea-floor spreading extended northwards into Rockall Trough. Ocean-floor formation in the Bay of Biscay and Rockall Trough stopped at about 84 Ma but the ocean continued to open between Britain and Newfoundland.

After the cessation of spreading in the Rockall Trough, the axis of break-up shifted westwards into the Labrador Sea. Although the crust between Greenland and Labrador had been stretching and subsiding since about 125 Ma (Balkwill, 1987), uncertainties in the interpretation of magnetic anomalies in the region have led to some debate over the timing of the initiation of active sea-floor spreading. Roest & Srivastava (1989) have suggested that this started as early as 84 Ma but Chalmers & Laursen (1995) have shown that the oldest unambiguous magnetic anomalies imply a much later start (61 Ma). However, it is clear that by 61 Ma, the Mid-Atlantic Ridge was propagating northwards between Greenland and Labrador (Fig. 3).

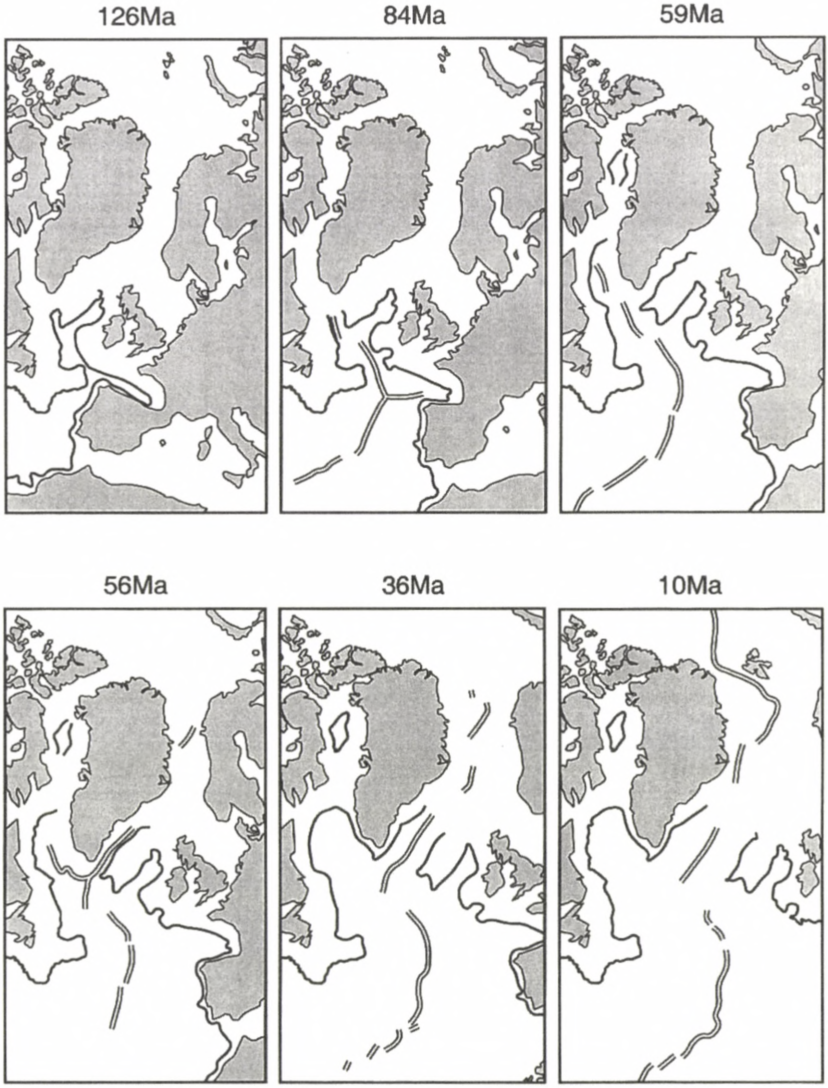

Figure 3. Reconstructions of the North Atlantic region, after Srivastava & Tapscott (1986). Present-day coastlines are shown for reference, and the edges of the continental shelves are represented by present-day 2000-m water-depth contours (thick lines). Sea-floor spreading ridges (double lines) are marked only where their positions are well constrained by magnetic anomalies.

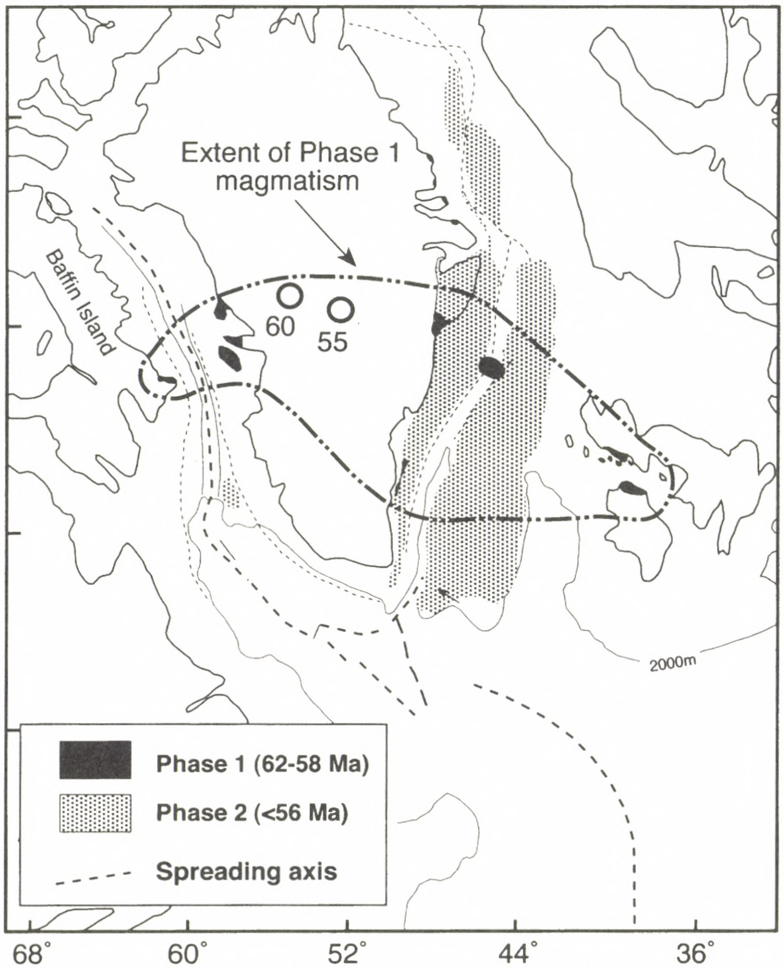

Figure 4. Reconstruction of the North Atlantic region at ~60 Ma showing the distribution of thick successions of volcanic rocks erupted at around that time. Phase 1 lava flows were erupted in response to the initiation of the Iceland mantle plume, and Phase 2 to the separation of Greenland from Western Europe. The circles labelled 55 and 60 show Lawver & Müller's (1994) calculated locations of the centre of the Iceland plume at 55 and 60 Ma respectively. After Saunders *et al*. (1997).

The later phase (62 Ma to the present)

A geological event occurred at ~62 Ma that was to change the course of history in the North Atlantic region, the effects of which had a lasting impact on the natural environment and economic development of north-

Figure 5. Eastern edge of the Palaeocene lava plateau on the Isle of Skye, Scotland. The photograph was taken looking southwards from Quirang. Horizontal basaltic lava flows of Phase 1 (Fig. 4) are exposed in escarpments formed by landsliding. (*Godfrey Fitton*)

west Europe. Up until this time the break-up of the continents had progressed from sedimentary basins to sea-floor spreading with volcanic activity confined to the actual spreading axes of the new ocean basins. But between 62 and 58 Ma the North Atlantic region saw a massive flare-up of volcanic activity across an area extending ~2000 km from Arctic Canada to Scotland (Fig. 4; Chalmers *et al.*, 1995). Flood basalts of this age are found in Baffin Island (Clarke & Upton, 1971), West Greenland (Clarke & Pedersen, 1976), East Greenland (Larsen & Saunders, 1998), Northern Ireland, and Scotland (Fig. 5; Emeleus & Gyopari, 1992). Volcanism on this scale requires a sudden increase in the temperature of the mantle beneath the region, and the most plausible reason for this is the initiation of the mantle plume now situated beneath Iceland.

Mantle plumes are the principal expression of convection from the deep mantle, and the resulting flow of shallow asthenosphere away from plume axes provides some of the force that moves the lithospheric plates. The plume beneath Iceland today has recently been imaged seismically and is seen to have a radius of ~150 km (Wolfe *et al.*, 1997) and to originate at a depth of >660 km in the mantle (Shen *et al.*, 1998). At the time of its origin, however, the plume is likely to have developed a large mushroom-like head extending over a radius of ~1000 km (e.g. Richards *et al.*, 1989). Past positions of the plume axis with respect to the continents can be reconstructed from known plate motions, and it is likely to have been close to West Greenland at ~62 Ma (Lawver & Müller, 1994).

We can not be certain of the extent to which the plume influenced the break-up of the North Atlantic region, but sea-floor spreading started between Greenland and Norway soon after its arrival (Fig. 3). Spreading in the Labrador Sea continued at a reduced rate until ~36 Ma, but the main axis of plate separation moved to the east of Greenland at ~56 Ma. The separation of Greenland from north-west Europe was accompanied by a second and even more intense phase of magmatism (Saunders *et al.*, 1997), this time producing thick piles of flood basalt along the East Greenland coast (e.g. Larsen *et al.*, 1989; Fig. 6) and the Faeroes (Waagstein, 1988) and even thicker and more extensive successions of basalt offshore on the Rockall Plateau (Ritchie & Hitchen, 1996) and along the continental shelves of Greenland and Norway (Fig. 4). The international Ocean Drilling Program has recently sampled a

Figure 6. Plateau lavas (Skrænterne Formation) of Phase 2 in the area south of Scoresby Sund, East Greenland. (*Danish Lithosphere Centre*)

Figure 7. Layers of basaltic ash (black) in the mo-clay at Hanklit on the island of Mors, Jutland. The rocks exposed in this cliff section have been overturned in places through the action of advancing ice sheets during the Ice Age. (*Godfrey Fitton*)

transect across the submerged volcanic successions off south-east Greenland as part of a multidisciplinary research programme initiated by the Danish Lithosphere Centre (Larsen & Saunders, 1998; Fitton *et al.,* 2000).

Basaltic volcanism at mid-ocean ridges and above mantle plumes is rarely as explosive as the volcanic eruptions at destructive plate margins. This is because basaltic magma is less viscous and has a lower content of dissolved volatile material than does the more silica-rich magma typical of subduction zones. However, the post-break-up volcanism off East Greenland was an exception to this rule. Basaltic ash from this phase of volcanic activity blanketed large areas of western Europe and is preserved in the sedimentary record of the North Sea and adjacent areas (Knox & Morton, 1988). These ashes are best preserved in the mo-clay of northern Jutland (Fig. 7) where about 180 individual ash layers with a total thickness of several metres have been recorded (Bøggild, 1918). It seems likely that unusually vigorous eruption of basaltic magma at the time of continental separation, coupled with the interaction between these magmas and sea water, was responsible for this explosive volcanism. The mo-clay in which the Danish ashes occur contains fossils that place the time of eruption precisely at the Palaeocene-Eocene boundary. Radiometric dating techniques can rarely be used to measure the ages of fossils and sedimentary rocks directly, but these can readily be applied to volcanic rocks. The Danish ashes have considerable stratigraphic value in providing the absolute age (55 Ma) of the Palaeocene-Eocene boundary used in the international geological time scale (Berggren *et al.*, 1995).

The cessation of sea-floor spreading in the Labrador Sea at ~36 Ma left only one spreading axis active during the final stages of opening of the North Atlantic Ocean. This axis propagated rapidly northwards between Greenland and Norway and into the Arctic Ocean after ~56 Ma and is still active today. Although the two halves of the North Atlantic Ocean are spreading symmetrically, the whole region is drifting slowly to the north-west with respect to the Iceland plume. The plume axis would have crossed the East Greenland coast at 40 to 35 Ma (Lawver & Müller, 1994) and reached the Mid-Atlantic Ridge at ~25 Ma (Vink, 1984). Since ~25 Ma, the ridge has remained locked over the plume axis, and Iceland has formed as a result of the interaction between the plume and the Mid-Atlantic Ridge. Hotter mantle leads to more extensive melting beneath the section of ridge affected by the plume and to thickened oceanic crust beneath Iceland. The spreading ridge system in Iceland continues to drift north-westwards with respect to the plume axis but is periodically recaptured by the plume (Hardarson *et al.*, 1997). As a result, the oldest rocks in Iceland (15 Ma) are exposed in the far north-west of the island.

Economic and environmental impact of the Iceland plume

Were it not for the initiation of the Iceland plume, the North Atlantic region would have been very different today. Clearly Iceland would not exist, and it is likely that the North Atlantic Ocean would have opened between Greenland and Labrador. Greenland would then have been attached to western Europe and separated from Britain and Norway by extensions of the North Sea. In addition to these effects on the geography of the region, the Iceland plume has had other significant but less obvious environmental and economic consequences. We can only speculate on the environmental effects of the massive volcanic eruptions accompanying the separation of Greenland from Scotland at the end of the Palaeocene. These covered north-west Europe with volcanic ash and may have had a dramatic effect on the climate. Some idea of the magnitude of the environmental impact of these eruptions may be gained from the 1783 eruption of Laki, the largest historic eruption in Iceland. Volcanic gas and ash killed livestock throughout Iceland, with the consequent death by starvation of about one fifth of the Icelandic population, and the same eruption disturbed the climate of northern Europe and the eastern United States for the rest of the decade (Sigurdsson, 1982). The Late Palaeocene eruptions were very much larger and may have triggered climatic changes on a global scale. It may be significant that global climatic change and mass extinction of deep-water marine fauna at the end of the Palaeocene (Kennett & Stott, 1991) coincided exactly with the eruption of the ash layers preserved in north-west Europe.

Mantle plumes exert dynamic uplift on the overlying lithosphere, and the initiation of the Iceland plume caused widespread uplift of the North Atlantic region. Uplift leads to increased erosion and the resulting debris is ultimately deposited in sedimentary basins. The material eroded off Scotland in the Palaeocene, for example, was deposited in the North Sea and in the basins to the west of Shetland as laterally extensive sand bodies that acted as reservoir rocks for hydrocarbon deposits (White & Lovell, 1997). In addition to providing reservoir rocks, the Iceland plume may also have supplied some of the heat necessary for the maturation of hydrocarbon deposits (Green *et al.*, 1993)

Those parts of Greenland and Scotland uplifted during the initiation of the Iceland plume should have subsided rapidly as the continents drifted apart and moved away from the plume axis, but this is not so. The extra loading of up to 7 km of basalt in East Greenland (Pedersen *et al.*, 1997) ought to have depressed the pre-uplift land surface but instead this surface has remained elevated. Deep-marine Mesozoic sediments deposited in the basin between Greenland and Norway are exposed beneath the lava pile at several localities in East Greenland (Soper *et al.*, 1976), implying considerable uplift of the continental margin. In this context it should be noted that the highest point in Greenland, Gunnbjørn Fjeld, is close to the East Greenland coast. A similar situation exists in Scotland, where the highest ground is in the west and Mesozoic marine sediments are exposed beneath Palaeocene basaltic lava flows in the Hebrides. This permanent uplift of the continental margins of north-western Europe and East Greenland implies the emplacement of igneous rocks at the base of the crust that more than compensate for the loading imposed by the eruption of basaltic lavas on the surface. There is good geophysical evidence for the existence of such material beneath both continental margins (White *et al.*, 1987; Larsen *et al.,* 1998). Although an enormous volume of magma was erupted during the final break-up of the North Atlantic region, a considerably larger volume cooled and crystallised at the base of the crust through a process known as underplating.

Uplift of continental margins through underplating of the crust with igneous material produces half-dome structures with radial drainage patterns that can survive for up to 200 million years after continental rupture (Cox, 1989). Such a half dome is apparent in the topography of Greenland when the ice is removed and the surface elevation corrected for the isostatic effects of ice loading (Letréguilly *et al.*, 1991). The resulting map shows an elongate elevated region extending along the whole of East Greenland and centred on that part of the continental margin where the Iceland plume passed from beneath the continent to the ocean (Lawver & Müller, 1994). Part of a complementary half dome can be seen on the other side of the North Atlantic in the topography of Scotland, with its spectacular western coast, and rivers that drain to the east. It is likely that the whole of Britain was tilted through underplating of north-western Scotland during the Palaeocene (Brodie & White, 1994). The activity of the Iceland plume ~60 million years ago was therefore instrumental in shaping the present landscape on both sides of the North Atlantic Ocean. But for the Iceland plume, Scotland would probably have no mountains today.

Acknowledgements

We thank John Maclennan for Figure 1, Andy Saunders for Figure 4, and Gerry White for drafting Figures 2 and 3.

Lotte Melchior Larsen publishes with the permission of the Geological Survey of Denmark and Greenland.

References

Balkwill, H. R. (1987). Labrador basin: structural and stratigraphic style. In: Beaumont, C. & Tankard, A. J. (eds), *Sedimentary basins and basin-forming mechanisms*. Canadian Society of Petroleum Geologists, Memoir 12, 17-43.

Berggren, W. A., Kent, D. V., Swisher, C. C. III & Aubry, M.-P. (1995). A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W. A., Kent, D. V., Aubry, M.-P. & Hardenbol, J. (eds), *Geochronology, Time Scales and Global Stratigraphic Correlation*, Society of Economic Paleontologists and Mineralogists Special Publications 54, 129-212.

Bøggild, O. B. (1918). Den vulkanske aske i Moleret samt en oversigt over Danmarks Ældre Tertiærbjergarter. *Danmarks Geologiske Undersøgelse, Række 2*, 33, 159 pp.

Brodie, J. & White, N. (1994). Sedimentary basin inversion caused by igneous underplating: Northwest European continental shelf. *Geology*, 22, 147-150.

Chalmers, J. A. & Laursen, K. H. (1995). Labrador Sea: the extent of continental and oceanic crust and the timing of the onset of seafloor spreading. *Marine and Petroleum Geology,* 12, 205-217.

Chalmers, J. A., Larsen, L. M. & Pedersen, A. K. (1995). Widespread Palaeocene volcanism around the northern North Atlantic and Labrador Sea: evidence for a large, hot, early plume head. *Journal of the Geological Society, London*, 152, 965-969.

Clarke, D. B. & Pedersen, A. K. (1976). Tertiary volcanic province of West Greenland. In: Escher, A. & Watt, W. S. (eds), *Geology of Greenland*. The Geological Survey of Greenland, Copenhagen, 365-385.

Clarke, D. B. & Upton, B. G. J. (1971). Tertiary basalts of Baffin Island: field relations and tectonic setting. *Canadian Journal of Earth Sciences*, 8, 248-258.

Cox, K. G. (1989). The role of mantle plumes in the development of continental drainage patterns. *Nature*, 342, 873-877.

Darbyshire, F. A., Bjarnason, I. T., White, R. S. & Flovenz, O. G. (1998). Crustal structure above the Iceland mantle plume imaged by the ICEMELT refraction profile. *Geophysical Journal International*, 135, 1131-1149.

Emeleus, C. H. & Gyopari, M. C. (1992). *The British Tertiary Volcanic Province*. Chapman and Hall, London, 259 pp.

Fitton, J. G., Larsen, L. M., Saunders, A. D., Kempton, P. D. & Hardarson, B. S. (2000). Palaeogene continental to oceanic magmatism on the south-east Greenland continental margin at 63°N: a review of the results of Ocean Drilling Program Legs 152 and 163. *Journal of Petrology,* 41, 951-966.

Green, P. F., Duddy, I. R., Bray, R. J. & Lewis, C. L. E. (1993). Elevated palaeotemperatures prior to Early Tertiary cooling throughout the UK region: Implications for hydrocarbon generation. In: Parker, J. R. (ed.), *Petroleum Geology of NW Europe: Proceedings of the 4th Conference*, Geological Society, London, 1067-1074.

Hardarson, B. S., Fitton, J. G., Ellam, R. M & Pringle, M. S. (1997). Rift relocation – a geochemical and geochronological investigation of a palaeo-rift in NW Iceland. *Earth and Planetary Science Letters*, 153, 181-196.

Heezen, B. C., Tharp, M. & Ewing, M. (1959). *The Floors of the Oceans. I. The North Atlantic*. The Geological Society of America, Special Paper 65, 122 pp.

Hess, H. H. (1962). History of Ocean Basins. In: Engel, A. E. J., James, H. L. &

Leonard, B.F. (eds), *Petrologic Studies: A Volume to Honor A. F. Buddington*. Geological Society of America, New York, 599-620.

Holmes, A. (1931). Radioactivity and earth movements. *Transactions of the Geological Society of Glasgow*, 18, 559-606.

Kennett, J. P. & Stott, L. D. (1991). Abrupt deep-sea warming, paleoceanographic changes and benthic extinctions at the end of the Paleocene. *Nature*, 353, 225-229.

Knox, R. W. O'B. & Morton, A.C. (1988). The record of early Tertiary N Atlantic volcanism in sediments of the North Sea Basin. In: Morton, A. C. & Parson, L. M. (eds), *Early Tertiary Volcanism and the Opening of the NE Atlantic*, Geological Society, London, Special Publication 39, 407-419.

Larsen, H. C. & Saunders, A. D. (1998). Tectonism and volcanism at the southeast Greenland rifted margin: a record of plume impact and later continental rupture. *Proceedings of the Ocean Drilling Program, Scientific Results*, 152, 503-533.

Larsen, H. C., Dahl-Jensen, T. & Hopper, J. R. (1998). Crustal structure along the Leg 152 transect. *Proceedings of the Ocean Drilling Program, Scientific Results*, 152, 463-475.

Larsen, L. M., Watt, W. S. & Watt, M. (1989). Geology and petrology of the Lower Tertiary plateau basalts of the Scoresby Sund region, East Greenland. *Bulletin of the Geological Survey of Greenland,* 157, 164 pp.

Lawver, L. A., & Müller, R. D. (1994). Iceland hotspot track. *Geology*, 22, 311-314.

Letréguilly, A., Huybrechts, P. & Reeh, N. (1991). Steady-state characteristics of the Greenland ice sheet under different climates. *Journal of Glaciology*, 37, 149-157.

Menard, H. W. (1958). Development of median elevations in the ocean basins. *Bulletin of the Geological Society of America*, 69, 1179-1186.

Pedersen, A. K., Watt, M., Watt, W. S. & Larsen, L. M. (1997). Structure and stratigraphy of the Early Tertiary basalts of the Blosseville Kyst, East Greenland. *Journal of the Geological Society, London,* 154, 565-570.

Richards, M. A., Duncan, R. A. & Courtillot, V. E. (1989). Flood basalts and hot-spot tracks: plume heads and tails, *Science,* 246, 103-107.

Ritchie, J. D. & Hitchen, K. (1996). Early Palaeogene offshore igneous activity to the northwest of the UK and its relationship to the North Atlantic Igneous Province. In: Knox, R. W. O'B., Corfield, R. M. & Dunay, R. E. (eds.), *Correlation of the Early Paleogene in Northwest Europe*, Geological Society, London, Special Publication 101, 63-78.

Roest, W. R. & Srivastava, S.P. (1989). Sea-floor spreading in the Labrador Sea: a new reconstruction, *Geology*, 17, 1000-1003.

Saunders, A. D., Fitton, J. G., Kerr, A. C., Norry, M. J. & Kent, R. W. (1997). The North Atlantic Igneous Province. In: Coffin, M. F., and Mahoney, J. J. (eds.), *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood*

Volcanism. American Geophysical Union, Geophysical Monograph 100, 45-93.

Shen, Y., Solomon, S. C., Bjarnason, I. T. & Wolfe, C. J. (1998). Seismic evidence for a lower-mantle origin of the Iceland plume. *Nature*, 395, 62-65.

Sigurdsson, H. (1982). Volcanic pollution and climate: the 1783 Laki eruption. *Eos*, 63, 601-602.

Soper, N. J., Higgins, A. C., Downie, C., Matthews, D. W. & Brown, P. E. (1976). Late Cretaceous – early Tertiary stratigraphy of the Kangerdlugssuaq area, east Greenland, and the age of opening of the north-east Atlantic. *Journal of the Geological Society, London*, 132, 85-104.

Srivastava, S. P. & Tapscott, C. R. (1986). Plate kinematics of the North Atlantic. In: Vogt, P. R. & Tucholke, B. E. (eds), *The Geology of North America, Volume M, The Western North Atlantic Region*. Geological Society of America, 379-404.

Vine, F. J. & Matthews, D. H. (1963). Magnetic anomalies over ocean ridges. *Nature*, 199, 947-949.

Vink, G. E. (1984). A hotspot model for Iceland and the Vøring Plateau. *Journal of Geophysical Research*, 89, 9949-9959.

Waagstein, R. (1988). Structure, composition and age of the Faeroe basalt plateau. In: Morton, A. C. & Parson, L. M. (eds), *Early Tertiary Volcanism and the Opening of the NE Atlantic*, Geological Society, London, Special Publication 39, 225-238.

Wegener, A. (1915). *Die Entstehung der Kontinente und Ozeane*. F. Vieweg & Sohn, Braunschweig, Germany, 367 pp.

White N. & Lovell, B. (1997). Measuring the pulse of a plume with the sedimentary record, *Nature*, 387, 888-891.

White, R. S., Spence, G. D., Fowler, S. R., McKenzie, D., Westbrook, G. K. & Bowen, A. N. (1987). Magmatism at rifted continental margins. *Nature*, 330, 439-444.

White, R. S. (1997). Rift-plume interaction in the North Atlantic. *Philosophical Transactions of the Royal Society, London*, A, 355, 319-339.

Whittaker, R. C., Hamann, N. E. & Pulvertaft, T. C. R. (1997). A new frontier province offshore Northwest Greenland: structure, basin development and petroleum potential of the Melville Bay area. *American Association of Petroleum Geologists, Bulletin* 81, 978-998.

Wolfe, C. J., Bjarnason, I. T., VanDecar, J. C. & Solomon, S. C. (1997). Seismic structure of the Iceland mantle plume. *Nature,* 385, 245-247.

Ziegler, P. A. (1989). Evolution of the North Atlantic – an overview. In: Tankard, A. J. & Balkwill, H. R. (eds), *Extensional tectonics and stratigraphy of the North Atlantic Margins*. American Association of Petroleum Geologists, Memoir 46, 111-129.